On the fraction of star formation occurring in bound stellar clusters

(JMDK12, submitted)

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Introduction

Model

Applications

Conclusions

Why care about bound vs. unbound cluster formation?

- ✧ Affects efficiency of galactic scale feedback
  Strickland & Stevens 99, Hopkins+12, Krause+12
- ✧ Important when tracing galaxy evolution (e.g. SFH) using clusters
  Larsen+01, Bastian+05, Smith+07
- ✧ Crucial in understanding cluster formation and evolution
  Lada & Lada 03, Gieles+05, Elmegreen 08

QUESTION

How do star clusters form?

Or: what fraction of all stars is born in bound stellar clusters?

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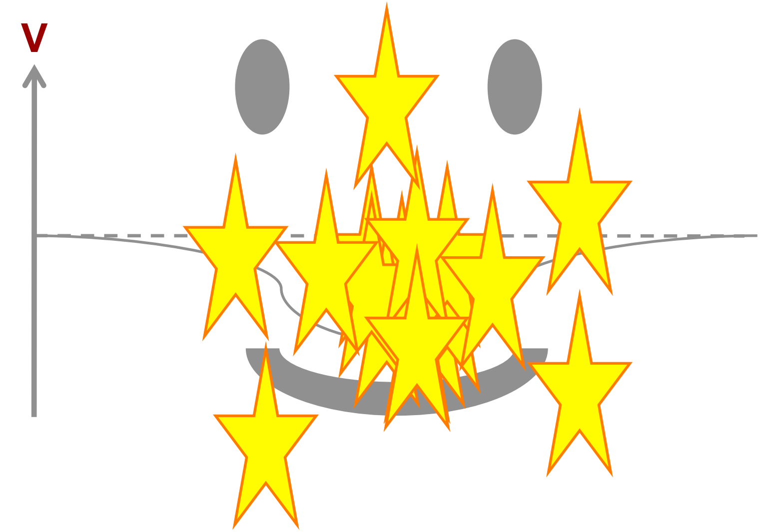
Star cluster formation: classical picture

✧ Classical picture: bound cluster formation inhibited by gas expulsion
Hills 80, Lada+84, Geyer & Burkert 01, Lada & Lada 03, Boily & Kroupa 03, Goodwin & Bastian 06, Baumgardt & Kroupa 07, Parmentier+08, …

✧ All stars form in clusters

✧ Gas & stars in virial equilibrium

✧ Feedback expels remaining gas



✧ Because SFE is low: cluster ***expands***, possibly becoming unbound

✧ Only ~10% of all star formation ends up in bound clusters

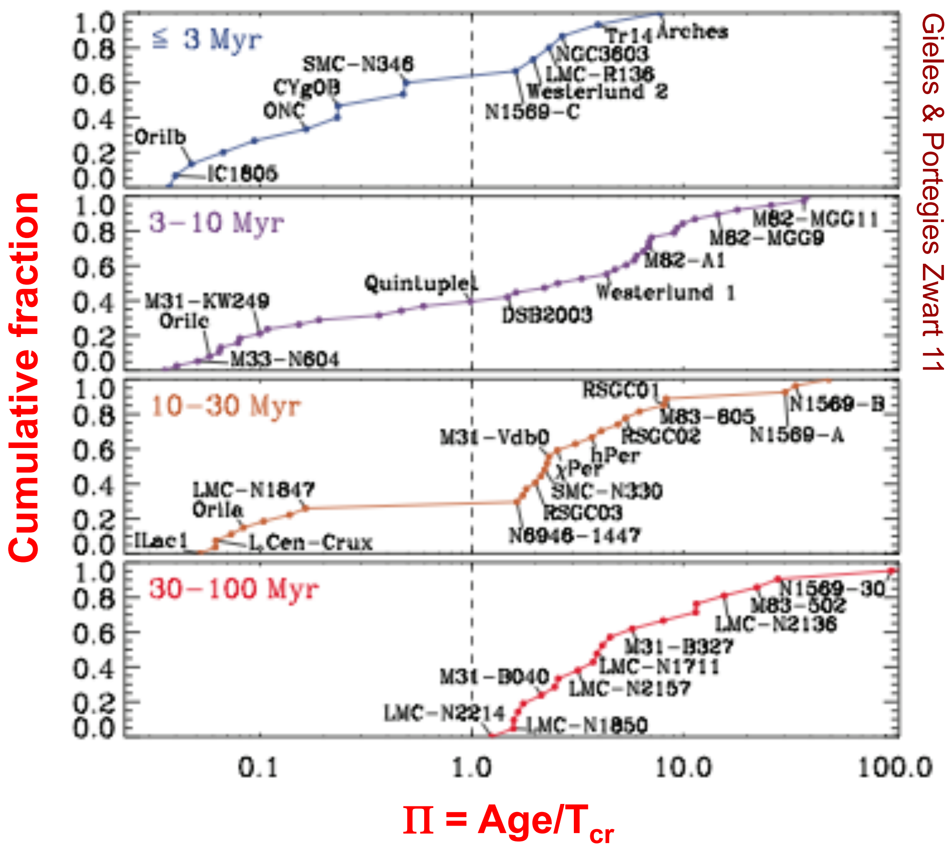
Little observational evidence for gas expulsion as key mechanism

- ✧ NGC 3603 is ~virialised and not expanding Rochau+10
- ✧ Westerlund I is ~virialised and not expanding Cottaar+12
- ✧ R136 is ~virialised and not expanding Hénault-Brunet+12
- ✧ Arches Cluster is ~virialised and not expanding Clarkson+12

Star cluster formation

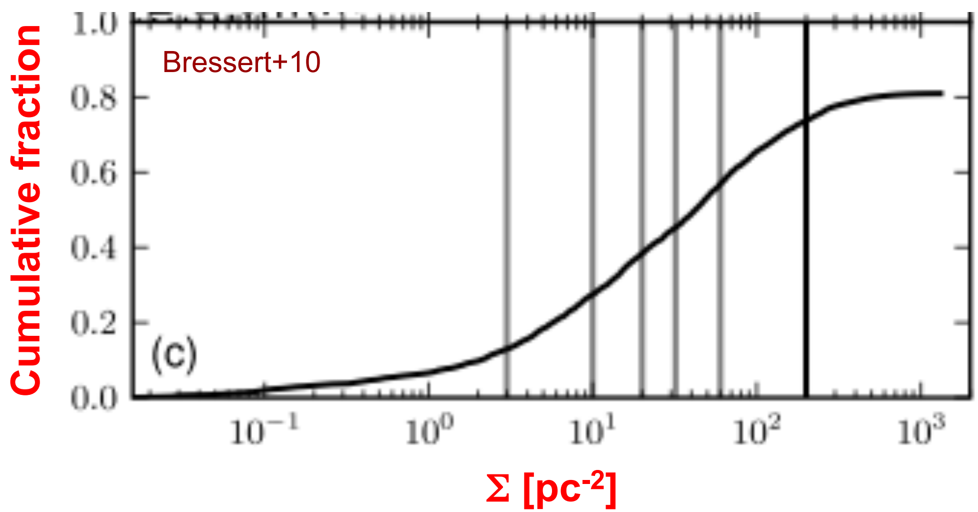
✧ Not all stars form in clusters

Bastian 08, Gieles & Portegies Zwart 11



Star cluster formation

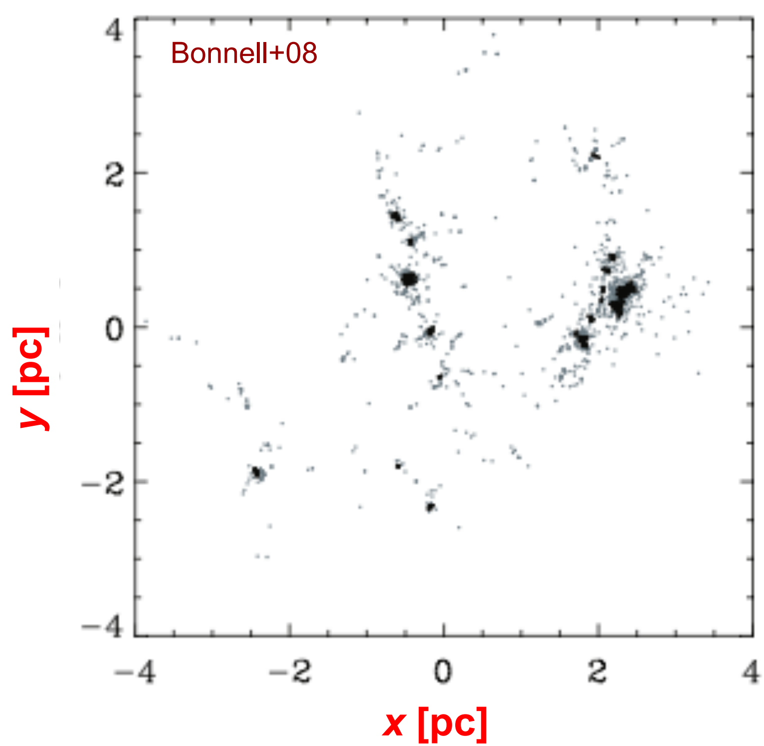
✧ Continuous density spectrum of star formation
Bressert+10

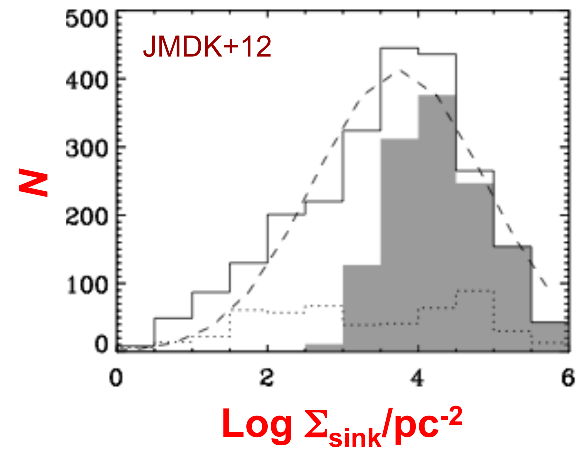


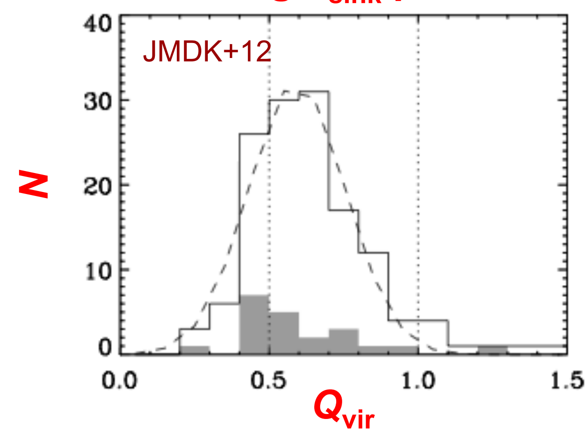
Star cluster formation

✧ Gas-poor & bound structure arises at the high-density end of the spectrum

Elmegreen 08, JMDK+12, Girichidis+12

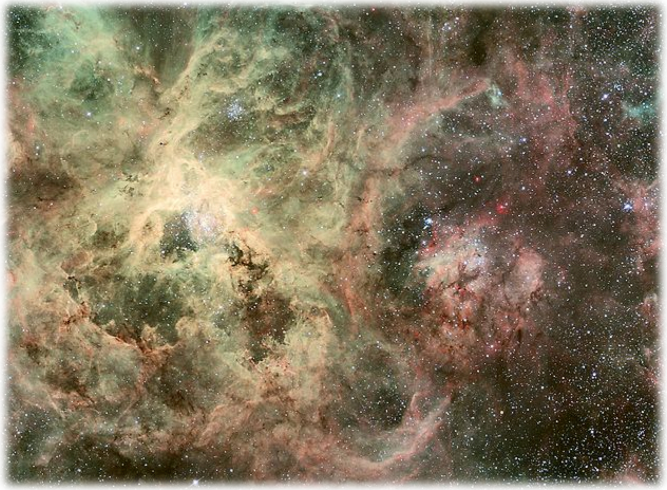






Star cluster formation

- ✧ No “infant mortality” by gas expulsion
- ✧ Star clusters are not a “fundamental unit of star formation”
- ✧ Star formation process is (initially) globally scale-free



So… what *does* happen?

Can we derive a theoretical framework for the *cluster formation efficiency*?

Introduction
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A “Dutch cheese” model

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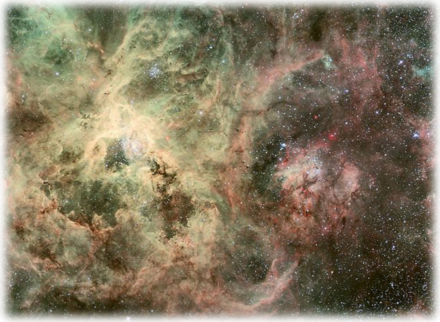
Two important mechanisms

- ✧ The naturally bound/unbound part of star formation
- ✧ The cruel cradle effect



$$\Gamma = f_{\rm bound} f_{\rm cce}$$

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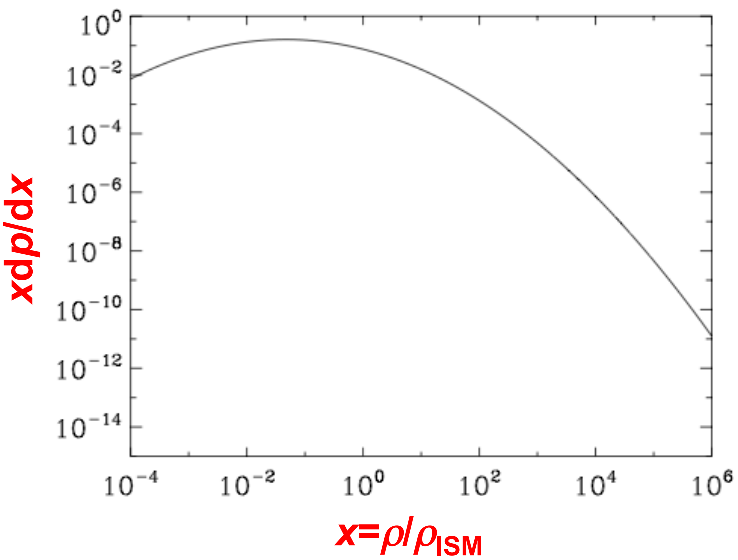
The model in one figure

- ✧ Overdensity PDF of the interstellar medium
  Vazquez-Semadini 94, Padoan & Nordlund 97,11

> ➢ **Surface density**
> ➢ **Angular velocity**
> ➢ **Toomre *Q* parameter**

- ✧ Mean and dispersion set by Mach number $\mathcal{M}(\Sigma_g,\Omega,Q)$



- ✧ Assuming hydrostatic equilibrium provides mid-plane density $\rho_{ISM}(\Omega,Q)$

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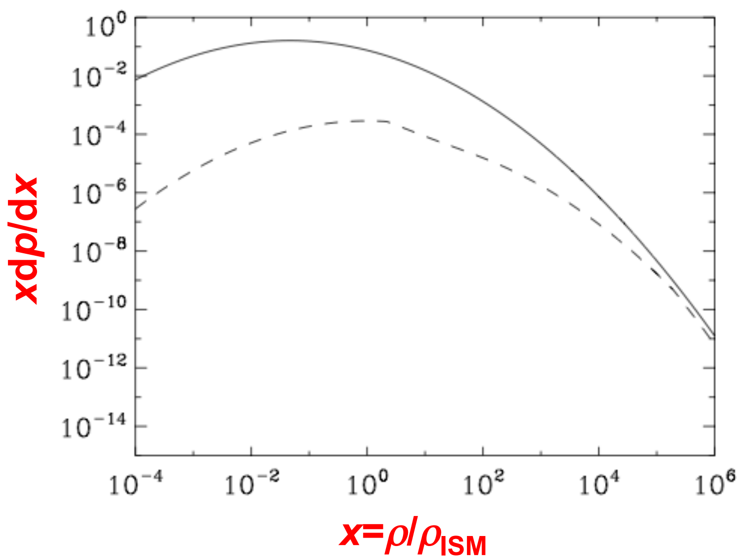
The model in one figure

✧ Assume specific SFR per free-fall time

Elmegreen 02, Krumholz & McKee 05

- Surface density
- Angular velocity
- Toomre *Q* parameter

✧ Pressure equilibrium between feedback and ISM gives duration of SF

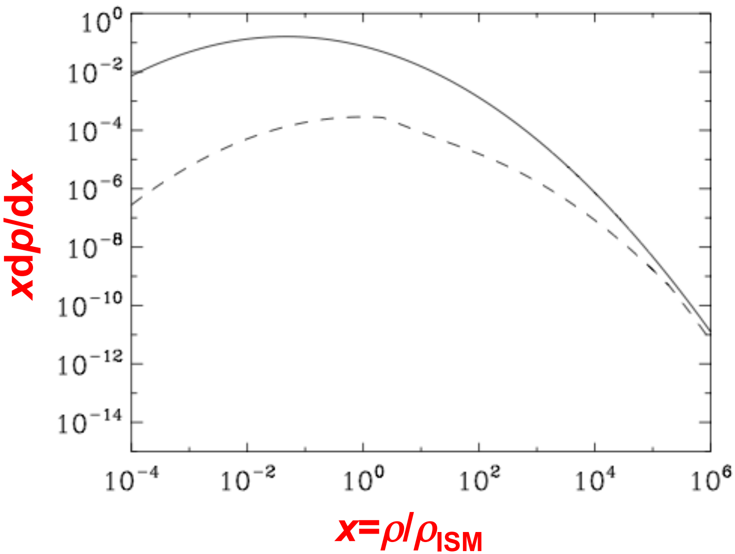


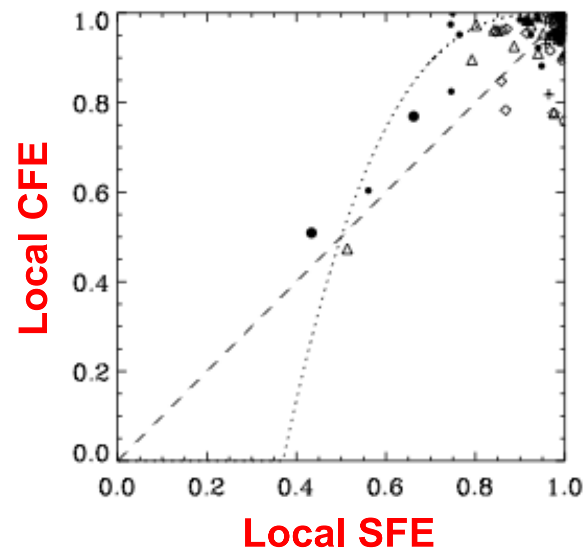
- Including the star formation efficiency

✧ Integration of dashed curve: all star formation

The model in one figure

- Surface density
- Angular velocity
- Toomre *Q* parameter





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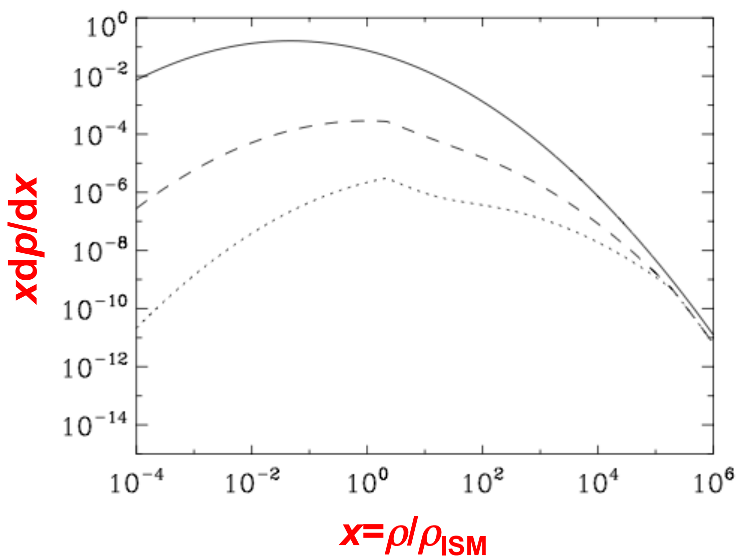
The model in one figure

- Surface density
- Angular velocity
- Toomre *Q* parameter



- Including the star formation efficiency
- Including naturally bound star formation

✧ Integration of dotted curve: naturally bound part of star formation

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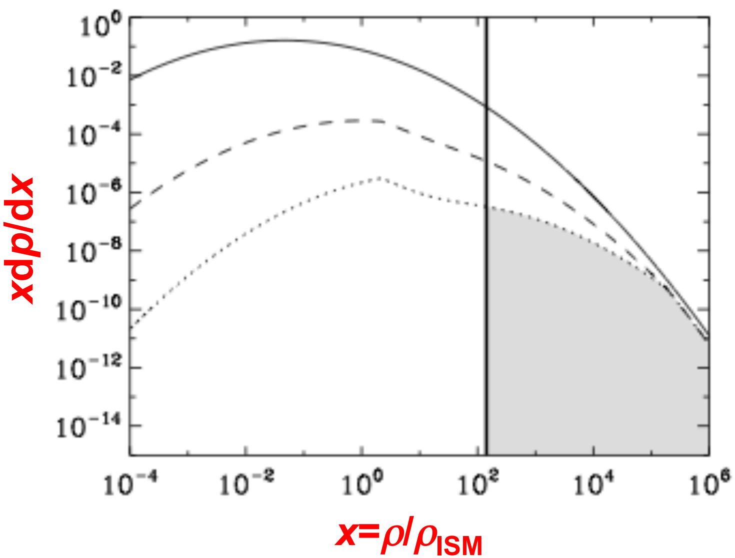
The model in one figure

✧ Cruel cradle effect: Spitzer theory of tidal shocks

- ➢ **Surface density**
- ➢ **Angular velocity**
- ➢ **Toomre *Q* parameter**

✧ Critical overdensity for surviving tidal disruption by SF environment



- ➢ **Including the star formation efficiency**
- ➢ **Including naturally bound star formation**
- ➢ **Including the cruel cradle effect**

✧ Integration gives the total cluster formation efficiency

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We now have the *global* CFE as a function of:

gas surface density
angular velocity
Toomre Q parameter

or *locally* as a function of:

gas volume density
gas velocity dispersion
sound speed

The fraction of star formation occurring in bound clusters

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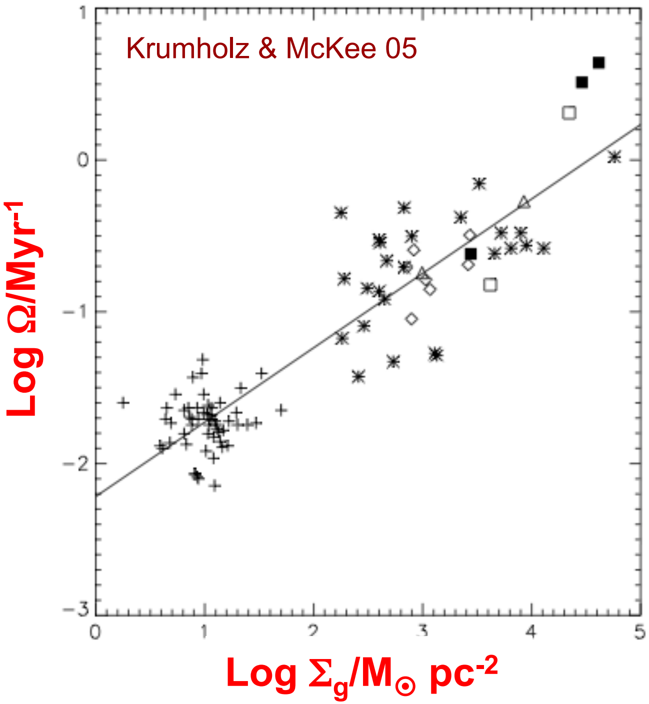
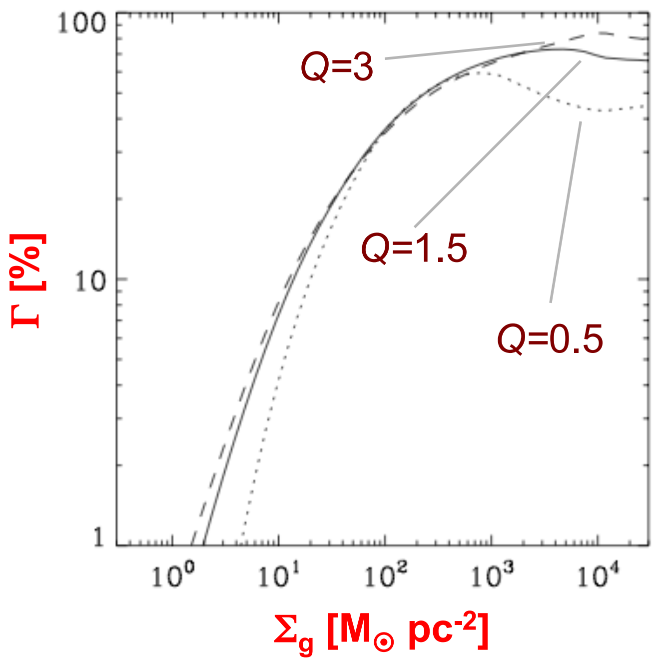
CFE as a function of… galaxy

- Need surface density, angular velocity and Toomre Q
- Q = {0.5,1.5,3} for {starburst,disc,quiescent}

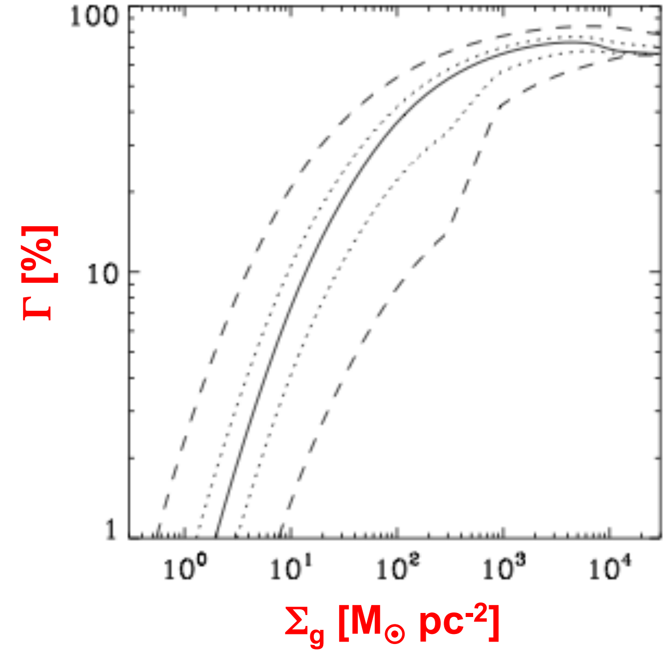




Dutch cheese revisited: model uncertainties

✧ Do the holes matter?

Parameter (1)	Minimum (2)	Maximum (3)	Impact on CFE (4)
ϕ_P	1	6	+
$\alpha_{\rm vir}$	1	2	+
$t_{\rm sn}$	2 Myr	5 Myr	+
t	5 Myr	20 Myr	−
$\phi_{\rm fb}$	0.032 $\rm cm^2\ s^{-3}$	0.8 $\rm cm^2\ s^{-3}$	+
$\epsilon_{\rm core}$	0.25	0.75	−
f	0.5	0.9	−
g	1	2	−
$\phi_{\rm sh}$	2	3	−
$\Sigma_{\rm GMC}^{\rm LG}$	30 $\rm M_\odot\ pc^{-2}$	300 $\rm M_\odot\ pc^{-2}$	−



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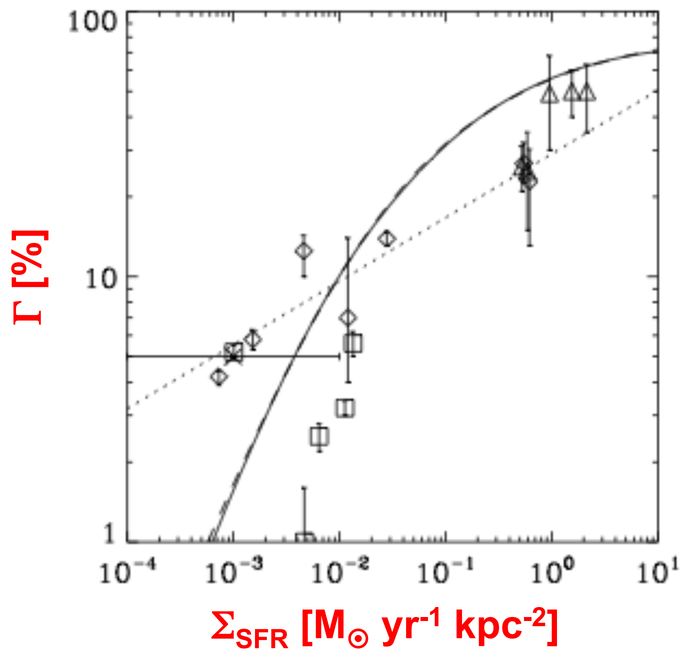
Comparison to nearby dwarf, spiral and starburst galaxies



Observations
Goddard+10
Silva-Villa+11
Adamo+11
Cook+12

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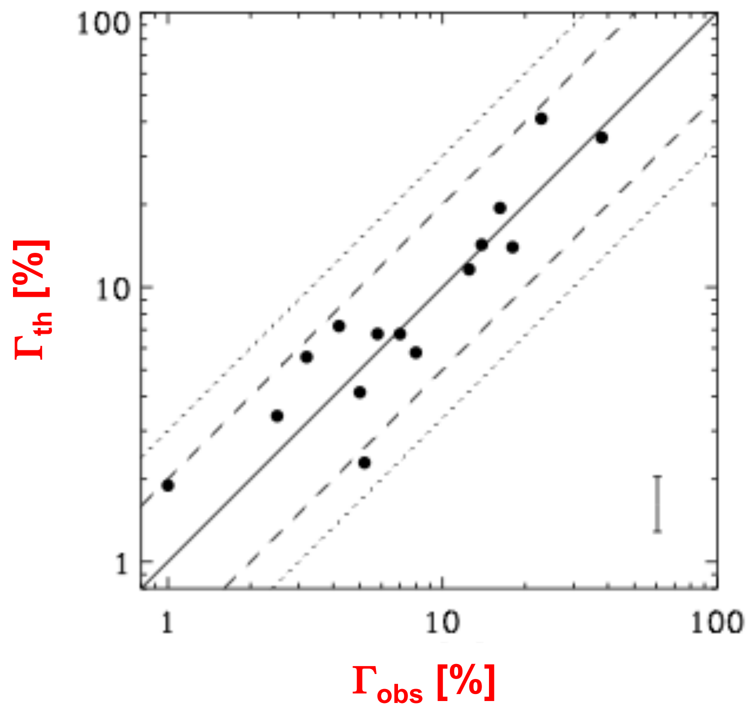
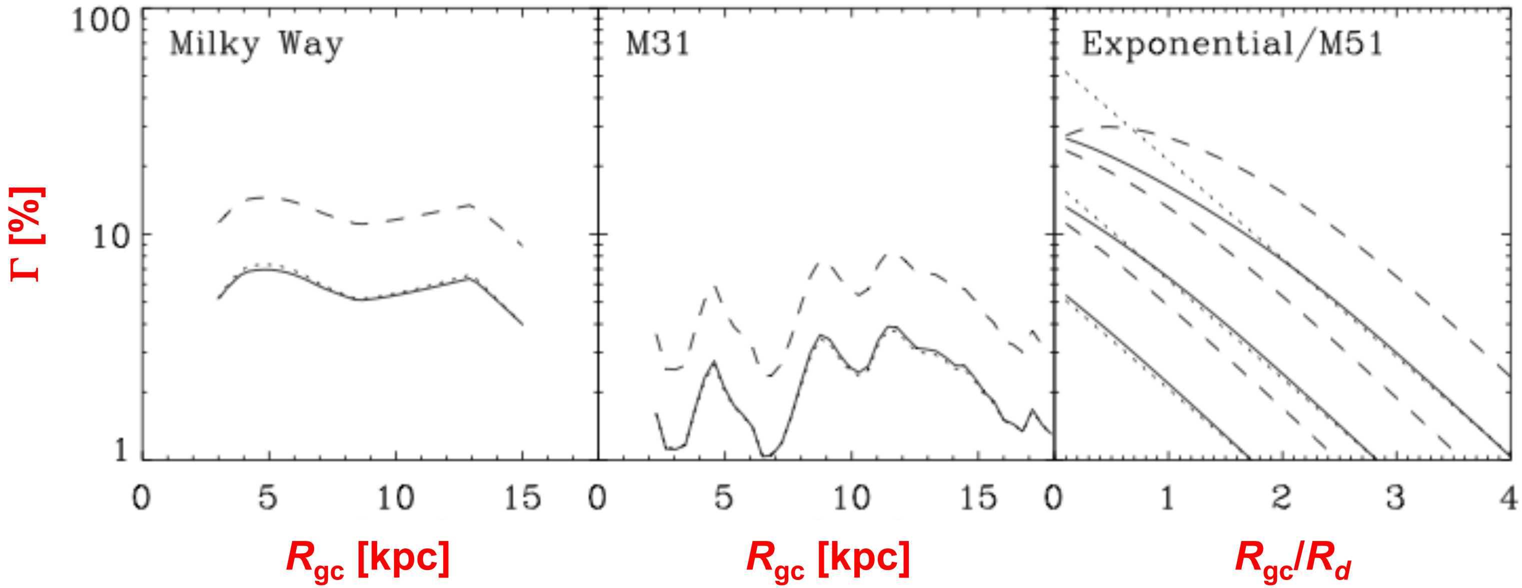
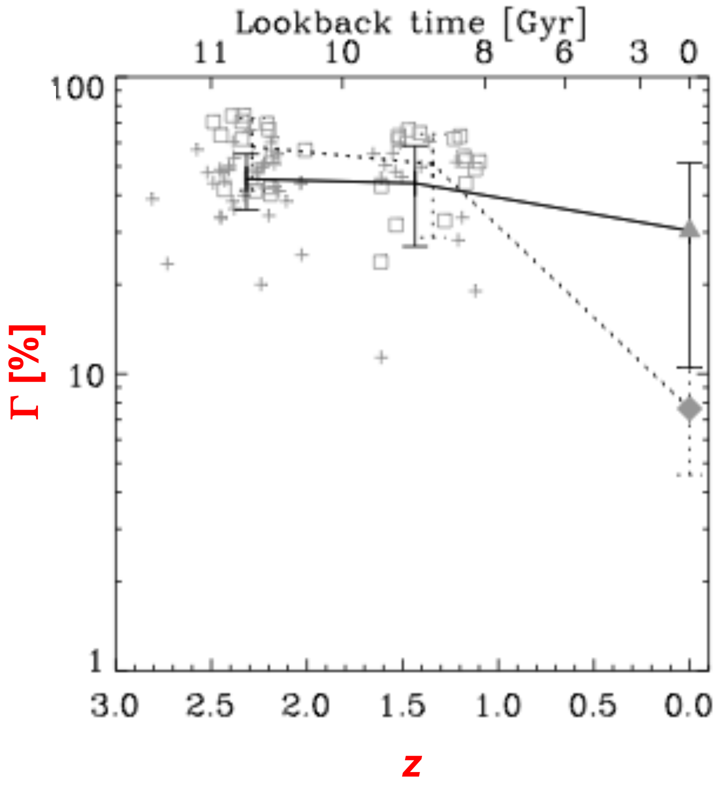


Spatially resolved cluster formation efficiency



Cosmic evolution of the cluster formation efficiency



Input from Observations
Kennicutt 98
Tacconi+08
Förster Schreiber+09
Tacconi+10
Genzel+10

$$\Gamma_{\rm univ} = 30\text{–}35\%$$

QUESTION

How do star clusters form?

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MODEL ANSWER

Star clusters form at the high-density tail of the ISM density spectrum

&

We can now predict the fraction of star formation that is clustered versus the fraction that is dispersed

OBSERVATIONS

Gaia **can verify whether gas expulsion acts on substructured (should) or collapsed, spherically symmetric (shouldn't) stellar structure**

&

Galactic ISM surveys should look for protoclusters and compare to the unembedded young cluster population

IMPLICATIONS

The information for the star cluster formation process is already present in the characteristics of the gas

&

Star clusters are no fundamental unit of star formation, but instead are a possible outcome

The fraction of star formation occurring in bound clusters

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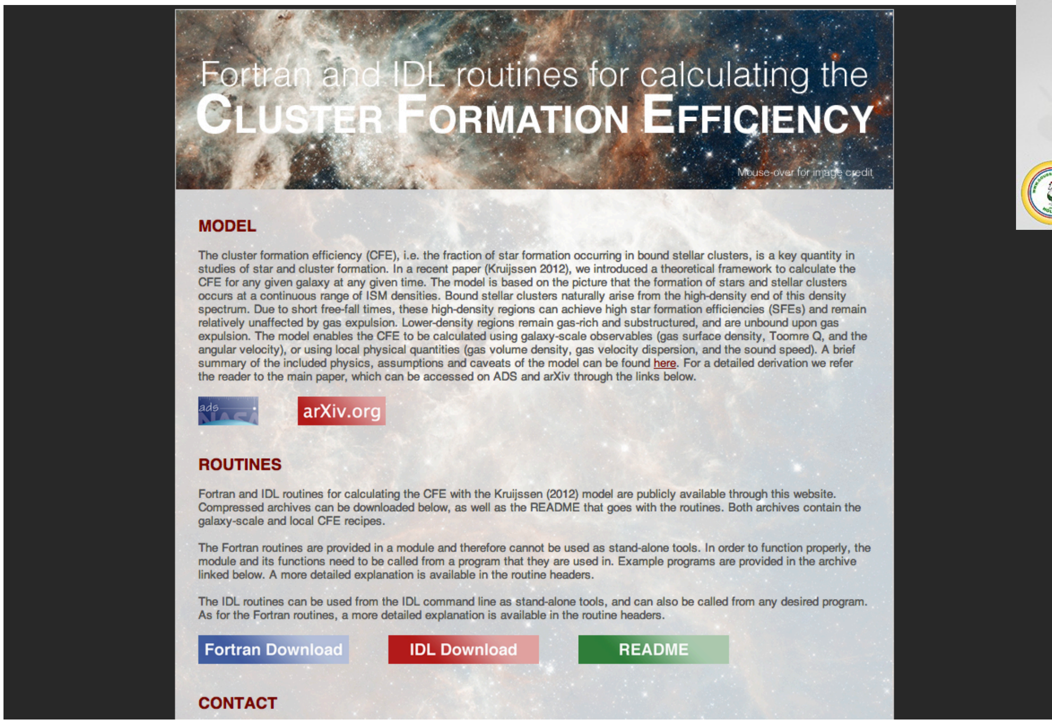
Feeling cheesy?



Publicly available Fortran and IDL routines upon paper acceptance

http://www.mpa-garching.mpg.de/cfe

(don't try, there's nothing there yet)